

FINAL REPORT
and
SUMMARY OF RESEARCH

ENTITLED

**LABORATORY EVALUATION AND APPLICATION OF MICROWAVE
ABSORPTION PROPERTIES UNDER SIMULATED CONDITIONS FOR
PLANETARY ATMOSPHERES**

to the

Planetary Atmospheres Program of the
National Aeronautics and Space Administration

For Grant NAG5-4190

Principal Investigator:

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Report Period: April 1, 1997 through December 31, 2001

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Table of Contents

	Page
I. INTRODUCTION AND SUMMARY	1
II. PROGRESS REPORT	1
III. STUDENTS SUPPORTED	2
IV. PUBLICATIONS	3
V. CONCLUSIONS	6
VI. APPENDIX	7

I. INTRODUCTION AND SUMMARY

Radio absorptivity data for planetary atmospheres obtained from spacecraft radio occultation experiments, entry probe radio signal absorption measurements, and earth-based or spacecraft-based radio astronomical (emission) observations can be used to infer abundances of microwave absorbing constituents in those atmospheres, as long as reliable information regarding the microwave absorbing properties of potential constituents is available. The use of theoretically-derived microwave absorption properties for such atmospheric constituents, or the use of laboratory measurements of such properties taken under environmental conditions that are significantly different than those of the planetary atmosphere being studied, often leads to significant misinterpretation of available opacity data. Laboratory measurements completed under this grant (NAG5-4190), have shown that the centimeter-wavelength opacity from gaseous phosphine (PH_3) under simulated conditions for the outer planets far exceeds that predicted from theory over a wide range of temperatures and pressures. This fundamentally changed the resulting interpretation of Voyager radio occultation data at Saturn and Neptune. It also directly impacts planning and scientific goals for study of Saturn's atmosphere with the Cassini Radio Science Experiment and the Cassini RADAR instrument. The recognition of the need to make such laboratory measurements of simulated planetary atmospheres over a range of temperatures and pressures which correspond to the altitudes probed by both radio occultation experiments and radio astronomical observations, and over a range of frequencies which correspond to those used in both spacecraft entry probe and orbiter (or flyby) radio occultation experiments and radio astronomical observations, has led to the development of a facility at Georgia Tech which is capable of making such measurements. It has been the goal of this investigation to conduct such measurements *and* to apply the results to a wide range of planetary observations, both spacecraft and earth-based, in order to determine the identity and abundance profiles of constituents in those planetary atmospheres.

II. PROGRESS REPORT

This project represents the latest stage of an ongoing activity begun in February 1984 to conduct laboratory measurements of the microwave and millimeter-wave properties of simulated planetary atmospheres, in support of NASA missions and ground-based microwave and millimeter-wave observations of planetary atmospheres. The project has also included application of the laboratory results to data from missions (such as Voyager) and earth-based observations (such as those from the NRAO/VLA), as well as direct involvement in mission-based microwave measurements and earth-based measurements.

From February 1984 through December 1996, this activity was supported by NASA Headquarters under Grant NAGW-533. Since April 1, 1997, this activity has been supported by Grant NAG5-4190 from the NASA Goddard Space Flight Center. A renewal proposal for FY 02 funding for this project (January 1, 2002 through December 31, 2002) was submitted to the NASA Planetary Atmospheres Program in May 2001, and

has been selected for funding in FY02-04. However, on May 2, 2002, we were formally notified of a change in policy at the NASA GSFC Grants Office, requiring that the renewal be in the form of a *new* grant (NAG5-12122), thus requiring this Summary of Research covering the period of the previous grant (NAG5-4190) from April 1, 1997 through December 31, 2001.

The technical progress of this project has been described in 5 Progress Reports submitted since 1997. Copies of all reports are available through the NASA Center for AeroSpace Information (NASA-CASI) and are on file at the Planetary Atmospheres Program Office. The current technical status of the project is described in the recent Proposal and Status Report #5 for Grant NAG5-4190, attached as Appendix A.

III. STUDENTS SUPPORTED

Over the course of this grant, numerous students have been supported as graduate research assistants. (See Table I.) Also included in Table I are the names of those students who conducted projects for academic credit in the area of this grant. Nearly every graduate student was involved in the publication of papers in either refereed journals or at conferences, such as AAS/DPS. (See Section IV.) Of the five Ph.D. students supported by this grant, two have gone on to permanent positions in planetary and space sciences. Two others have taken industry positions in space telecommunications. Titles of the Ph.D. dissertations are included in Section IV of this report.

TABLE I

Students supported by or conducting projects in the area of Grant NAG5-4190

Ph.D.

Marc A. Kolodner
Shady H. Suleiman
Scott A. Borgsmiller
James P. Hoffman
Priscilla N. Mohammed

B.S.

Ahmed N. Awa
Enrique Baez
Tanah L. Barchichat
William C. Barott
Keith C. Brouse
Christian F. Delaune
Adam Dittmer
Ho C. Ha
Stephen I. Halbgewachs

B.S. Students (con't)

Kenneth Lau
Keith L. Lee
T.H. Lin
Kristen May
Matthew Rehberg
Robert R. Riggsby
Antonio Serna
Chi Shum
Alan Smith
Bryan Sparks
Carlos Williams

IV. PUBLICATIONS

The following theses, journal publications, and conference presentations were supported (or partially supported) by Grant NAG5-4190.

Ph.D. Dissertations/Theses

Marc A. Kolodner (Ph.D. June 1997)

Thesis Title: Microwave Remote Sensing of Sulfuric Acid Vapor in the Venus Atmosphere.

Current Position: Research Scientist, Johns Hopkins University – Applied Physics Laboratory, Laurel, MD.

Shady H. Suleiman (Ph.D. June 1997)

Thesis Title: Microwave Effects of Gaseous Sulfur Dioxide (SO₂) in the Atmospheres of Venus and Earth.

Current Position: Member of the Technical Staff, TRW Space and Technology Division, Redondo Beach, CA.

Scott A. Borgsmiller (Ph.D. March 1998)

Thesis Title: Effects of Atmospheric Scintillation in Ka-Band Satellite Communications.

Current Position: Sr. Satellite Systems Engineer, COMSAT Laboratories, Clarksburg, MD.

James P. Hoffman (Ph.D. May 2001)

Thesis Title: Microwave Opacity of Phosphine: Application to Remote Sensing of the Atmospheres of the Outer Planets.

Current Position: RF Systems Engineer, Jet Propulsion Laboratory, Pasadena, CA.

Journal Publications

M. A. Kolodner and P.G. Steffes 1998. "The Microwave Absorption and Abundance of Sulfuric Acid Vapor in the Venus Atmosphere based on New Laboratory Measurements," *Icarus*, vol.132, pp. 151-169, March 1998.

J. P. Hoffman, P.G. Steffes, and D.R. DeBoer, "Laboratory Measurements of Phosphine's Microwave Opacity: Implications for Planetary Radio Science," *Icarus*, vol. 140, pp. 235-238, July 1999.

D.R. DeBoer and P. G. Steffes, "Performance and Uses of a Refurbished 30-m Former Satellite Communications Antenna: The Georgia Tech Woodbury Research Facility," *RadioScience*, vol. 34, pp. 991-1003, July-August 1999.

J.P. Hoffman, P.G. Steffes, and D.R. DeBoer, "The Microwave Absorption and Abundance of Phosphine in the Atmospheres of Saturn and Neptune Based on New Laboratory Measurements." *Icarus*, vol. 152, pp.172-184, July 2001.

B.J. Butler, P.G. Steffes, S.H. Suleiman, M.A. Kolodner and J.M. Jenkins, "Accurate and Consistent Microwave Observations of Venus and Their Implications." *Icarus*, vol. 154, pp. 226-238, December 2001

J.M. Jenkins, M.A. Kolodner, B.J. Butler, S.H. Suleiman, and P.G. Steffes, "Microwave Remote Sensing of the Thermal Structure and the Distribution of Sulfur Compounds in the Venus Atmosphere." *Icarus*, in press, 2002.

Conference Presentations with Published Proceedings or Abstracts

---S. A. Borgsmiller and P. G. Steffes, "Measurements of Ka-Band Amplitude and Phase Scintillation", Proceedings of the Twenty-First NASA Propagation Experimenters Meeting (NAPEX XXI). Presented at the NASA Propagation Experimenters Meeting (NAPEX XXI), El Segundo, CA, June 12, 1997.

---M. A. Kolodner, S. H. Suleiman, B. J. Butler, and P. G. Steffes. "Latitudinal Variations of Sulfur Compounds in the Venus Atmosphere Based on the Correlation between VLA Observations and Radio Occultation Results." *Bulletin of the American Astronomical Society* 29, 1042-1043. Presented at the 29th Annual Meeting of the division for Planetary Sciences of the American Astronomical Society, Cambridge, MA, August 1, 1997.

---J.P. Hoffman, P. G. Steffes, and D. R. DeBoer, Preliminary Results of Laboratory Measurements of the Centimeter Wavelength Properties of Phosphine under Simulated Conditions for the Outer Planets, "*Bulletin of the American Astronomical Society*, vol. 30 no. 3, 1998. p. 1102. Presented at the 30th Annual Meeting of the Division for Planetary Sciences of the American Astronomical Society, Madison, WI, October 15, 1998

---B.J. Butler, J.M. Jenkins, and P.G. Steffes, "Whole-disk Microwave Brightness Temperature Spectrum of Venus," *Bulletin of the American Astronomical Society*, vol. 30, no. 3, pp. 1105-

1106. Presented at the 30th Annual Meeting of the Division for Planetary Sciences of the American Astronomical Society, Madison, WI, October 16, 1998.

---J.M. Jenkins, B.J. Butler, P.G. Steffes, and M.A. Kolodner, "Retrievals of Sulfur-Bearing Gas Abundances from Microwave Emission Maps of Venus Obtained at the VLA," Bulletin of the American Astronomical Society, vol. 30, no. 4, pp. 1340. Presented at the 30th Annual Meeting of the Division for Planetary Sciences of the American Astronomical Society, Madison, WI, October 16, 1998.

---J.P. Hoffman and P.G. Steffes, "Preliminary Results of Laboratory Measurements of the Centimeter Wavelength Properties of Phosphine under Simulated Conditions for the Outer Planets," International Union of Radio Science Programs and Abstracts: 1999 National Radio Science Meeting, p. 286. Jan. 1999. Presented at the National Radio Science Meeting, Boulder, CO, January 7, 1999.

--J.P. Hoffman and P.G. Steffes, "Low Temperature Laboratory Measurements of the Centimeter Wavelength Properties of Phosphine under Simulated Outer Planet Conditions," Bulletin of the American Astronomical Society, vol. 31, no. 4, 1999. p. 1169. Presented at the 31st Annual Meeting of the Division for Planetary Sciences of the American Astronomical Society, Padova, Italy, October 14, 1999.

--P.G. Steffes, "Current Issues in Spectrum Management Affecting Radio Astronomy and Remote Sensing," International Union of Radio Science Programs and Abstracts: 2000 National Radio Science Meeting, p. 206, Jan. 2000. Presented at the National Radio Science Meeting, Boulder, CO, January 7, 2000.

---J.P. Hoffman and P.G. Steffes, "Laboratory Measurements of the Microwave Opacity of Phosphine: Opacity Formalism and Applications to the Atmospheres of the Outer Planets," Bulletin of the American Astronomical Society, vol. 32, no. 3, 2000. p. 1110. Presented at the 32nd Annual Meeting of the Division for Planetary Sciences of the American Astronomical Society, Pasadena, CA, October 26, 2000.

---P.G. Steffes, "Current Issues in Domestic Spectrum Management Affecting Radio Astronomy and Remote Sensing," International Union of Radio Science Programs and Abstracts: 2001 National Radio Science Meeting, p. 328, Jan. 2001. Presented at the National Radio Science Meeting, Boulder, CO, January 11, 2001.

---J.P. Hoffman and P.G. Steffes, "Laboratory Measurements of the Microwave Opacity of Phosphine: Opacity Formalism and Applications to the Atmospheres of the Outer Planets," Presented at the National Radio Science Meeting, Boulder, CO, January 9, 2001. (First Place for Hoffman in URSI Student Paper Competition.)

---J.P. Hoffman and P.G. Steffes, "Will Cassini Detect Phosphine? Results from a Ray Tracing Based Radiative Transfer Model of Saturn's Atmosphere," Bulletin of the American Astronomical Society, vol. 33, no. 3, 2001. p. 1045. Presented at the 33rd Annual Meeting of the Division for Planetary Sciences of the American Astronomical Society, New Orleans, LA, November 27, 2001.

---J.M Jenkins, M. A. Kolodner, B.J. Butler, S.H. Suleiman, and P.G. Steffes, "Microwave Remote Sensing of the Temperature and Distribution of Sulfur Compounds in the Lower Atmosphere of Venus," Bulletin of the American Astronomical Society, vol. 33, no. 3, 2001. p. 1038. Presented at the 33rd Annual Meeting of the Division for Planetary Sciences of the American Astronomical Society, New Orleans, LA, November 27, 2001.

---P.N. Mohammed and P.G. Steffes, "Preliminary Laboratory Measurements of the Millimeter Wavelength Properties of Phosphine (PH₃) under Simulated Outer Planet Conditions," Bulletin of the American Astronomical Society, vol. 33, no. 3, 2001. P. 1141. Presented at the 33rd Annual Meeting of the Division for Planetary Sciences of the American Astronomical Society, New Orleans, LA, December 1, 2001.

V. CONCLUSION

Over the 5-year duration of this grant, an effective program integrating microwave and millimeter-wave laboratory measurements with observations conducted from spacecraft experiments and earth-based radio astronomical observations has been conducted. Substantial new results regarding the nature and distribution of tropospheric constituents in the atmospheres of Venus and the outer planets have been obtained. It is expected that similar successes will continue as our new grant from NASA/GSFC commences.

NRA-01-01-PATM-009

Proposal Cover Page**NASA PROCEDURE FOR HANDLING PROPOSALS**

This proposal shall be used and disclosed for evaluation purposes only, and a copy of this Government notice shall be applied to any reproduction or abstract thereof. Any authorized restrictive notices that the submitter places on this proposal shall also be strictly complied with. Disclosure of this proposal for any reason outside the Government evaluation purposes shall be made only to the extent authorized by the Government.

NRA 01-OSS-01 PATM - Planetary Atmospheres and Planetary Suborbital Research**Proposed Principal Investigator:**

Dr. Paul G. Steffes

Georgia Institute of Technology

School of Electrical and Computer Engineering

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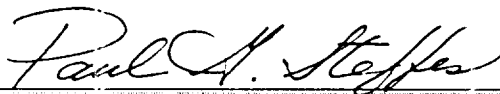
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PI Signature and Date:



May 17, 2001

Institution Authorization

Name of Authorizing Official: Janis L. Goddard

Title: Contracting Officer

Institution: Georgia Tech Research Corporation / Georgia Institute of Technology

Signature and Date:

Full TitleLaboratory Evaluation and Application of Microwave Absorption Properties
Under Simulated Conditions for Planetary Atmospheres**Short Title:** Laboratory Evaluation of Microwave Properties**Requested Funding & Duration**

Year One: \$ 99,959

Year Two: \$ 99,959

Year Three: \$ 99,959

Total: \$ 299,877

Duration: 3 years

Co-Investigators/Collaborators

NASA Grant or Contract Number of any current NASA award that the PI holds that is a logical predecessor of the newly proposed work
NAG5-4190

Type of Proposing Institution: Educational institution

Research Category: Interpretation of Data (including DA techniques)

Research Carrier: No

Technology Percentage: %

Themes

Theme 1: Solar System Exploration

Theme 2:

Theme 3:

Theme 4:

Program Area: Planetary Atmospheres - Laboratory Studies

Proposal Summary (Abstract)

Radio absorptivity data for planetary atmospheres obtained from spacecraft radio occultation experiments, entry probe radio signal absorption measurements, and earth-based radio astronomical observations can be used to infer abundances of microwave absorbing constituents in those atmospheres, as long as reliable information regarding the microwave absorbing properties of potential constituents is available. The use of theoretically-derived microwave absorption properties for such atmospheric constituents, or the use of laboratory measurements of such properties taken under environmental conditions that are significantly different than those of the planetary atmosphere being studied, often leads to significant misinterpretation of available opacity data. For example, new laboratory measurements completed recently by Hoffman, Steffes and DeBoer (2001) under this grant (NAG5-4190), have shown that the centimeter-wavelength opacity from gaseous phosphine (PH₃) under simulated conditions for the outer planets far exceeds that predicted from theory over a wide range of temperatures and pressures. This fundamentally changed the resulting interpretation of Voyager radio occultation data at Saturn and Neptune. It also directly impacts planning and scientific goals for study of Saturn's atmosphere with the Cassini Radio Science Experiment and the Cassini RADAR instrument. The recognition of the need to make such laboratory measurements of simulated planetary atmospheres over a range of temperatures and pressures which correspond to the altitudes probed by both radio occultation experiments and radio astronomical observations, and over a range of frequencies which correspond to those used in both spacecraft entry probe and orbiter (or flyby) radio occultation experiments and radio astronomical observations, has led to the development of a facility at Georgia Tech which is capable of making such measurements. It has been the goal of this investigation to

conduct such measurements and to apply the results to a wide range of planetary observations, both spacecraft and earth-based, in order to determine the identity and abundance profiles of constituents in those planetary atmospheres. In the 3-year program proposed, key activities will include laboratory measurements of the millimeter-wavelength opacity of phosphine (PH₃) under simulated conditions for the outer planets, and measurements of the centimeter wavelength opacity of HCl under Venus conditions.

Certification of Compliance with Applicable Executive Orders and U.S. Code

By signing and submitting the proposal identified in this Cover Sheet/Proposal Summary, the Authorizing Official of the proposing institution, as identified above (or the individual proposer if there is no proposing institution):

1. certifies that the statements made in this proposal are true and complete to the best of his/her knowledge;
2. agrees to accept the obligations to comply with NASA award terms and conditions if an award is made as a result of this proposal;
3. provides certification to the following that are reproduced in their entirety in this NRA: (i) Certification Regarding Debarment, Suspension, and Other Responsibility Matters; (ii) Certification Regarding Lobbying, and (iii) Certification of Compliance with the NASA Regulations Pursuant to Nondiscrimination in Federally Assisted Programs.

Done

Principal Investigator: Paul G. Steffes

Current Grant No: NAG5-4190 (This proposal serves also as Progress Report #5 for Grant NAG5-4190)

Title: Laboratory Evaluation and Application of Microwave Absorption Properties under Simulated Conditions for Planetary Atmospheres

I. INTRODUCTION AND SUMMARY

Radio absorptivity data for planetary atmospheres obtained from spacecraft radio occultation experiments, entry probe radio signal absorption measurements, and earth-based or spacecraft-based radio astronomical (emission) observations can be used to infer abundances of microwave absorbing constituents in those atmospheres, as long as reliable information regarding the microwave absorbing properties of potential constituents is available. The use of theoretically-derived microwave absorption properties for such atmospheric constituents, or the use of laboratory measurements of such properties taken under environmental conditions that are significantly different than those of the planetary atmosphere being studied, often leads to significant misinterpretation of available opacity data. For example, new laboratory measurements completed recently by Hoffman, Steffes and DeBoer (2001), under this grant (NAG5-4190), have shown that the centimeter-wavelength opacity from gaseous phosphine (PH_3) under simulated conditions for the outer planets far exceeds that predicted from theory over a wide range of temperatures and pressures. This fundamentally changed the resulting interpretation of Voyager radio occultation data at Saturn and Neptune. It also directly impacts planning and scientific goals for study of Saturn's atmosphere with the Cassini Radio Science Experiment and the Cassini RADAR instrument. The recognition of the need to make such laboratory measurements of simulated planetary atmospheres over a range of temperatures and pressures which correspond to the altitudes probed by both radio occultation experiments and radio astronomical observations, and over a range of frequencies which correspond to those used in both spacecraft entry probe and orbiter (or flyby) radio occultation experiments and radio astronomical observations, has led to the development of a facility at Georgia Tech which is capable of making such measurements. It has been the goal of this investigation to conduct such measurements *and* to apply the results to a wide range of planetary observations, both spacecraft and earth-based, in order to determine the identity and abundance profiles of constituents in those planetary atmospheres.

II. OUTER PLANETS STUDIES

A. Phosphine in the Atmospheres of the Outer Planets

In our past studies of the microwave emission spectrum of Neptune (DeBoer and Steffes, 1996a), we showed that in order to best match the most reliable disk-averaged emission measurements in the 1 mm to 20 cm range, and not exceed the measurements of 13 cm and 3.6 cm absorptivity made by Voyager 2 at Neptune (Lindal, 1992), a Neptune atmosphere where the abundance of H_2S is greater than that of NH_3 below the putative NH_4SH cloud in the deep atmosphere is required. While such an atmosphere (e.g. 78% H_2 , 19% He, 3% CH_4 , plus 40 x solar H_2S and 0.2 x solar NH_3) gives an excellent fit to the microwave emission spectrum, its opacity is too low at 13 cm and 3.6 cm to explain the Voyager radio occultation results. It was thought possible, however, to match both emission spectra and the Voyager results by adding phosphine (PH_3) to the model.

An even more compelling problem has been that the abundances of ammonia inferred by ascribing the microwave absorption measured by Voyager radio occultation experiments at Saturn (Lindal *et al.*, 1985) and Neptune (Lindal, 1992) to ammonia substantially exceed the saturation abundances for ammonia in those atmospheres (see Hoffman *et al.*, 2001), suggesting the presence of an additional source of microwave opacity such as PH_3 . Unfortunately, previous theoretical models of the centimeter-wavelength absorption from phosphine required extraordinarily large amounts of phosphine to explain the 13-cm and 3.6-cm absorption measured by Voyager at Saturn and Neptune. However, the actual opacity was thought to vary by an order of magnitude depending on which lineshape parameters and line intensities are used in the theoretical model. Thus to accurately infer the PH_3 abundance in the atmospheres of the outer planets from centimeter-wavelength microwave emission data (e.g. radio telescopic observations, or spacecraft radiometric measurements), from spacecraft radio occultation experiments (e.g. Voyager or Cassini at Saturn), and from entry probe uplink radio absorption data (e.g., Galileo at Jupiter) accurate laboratory measurements of phosphine's microwave opacity (and refractivity) were undertaken.

B. Completed Laboratory Measurements

In the past three years of our current grant (CY 1999 - 2001) the opacity and refractivity of two custom-manufactured (Matheson) gaseous mixtures consisting of 82.6% H_2 , 9.2% He, and 8.2% PH_3 (Mixture A) and 88.0% H_2 , 9.8% He, and 2.2% PH_3 (Mixture B) were measured at six frequencies (wavelengths): 1.5 GHz (20 cm), 2.25 GHz (13.3 cm), 8.3 GHz (3.6 cm), 13.3 GHz (2.3 cm), 21.7 GHz (1.38 cm), and 27 GHz (1.1 cm) at pressures from 1 to 6 Bars. The first frequency (1.5 GHz) is close to the Galileo Probe transmitter frequency, and our measurements have been of direct use in interpreting that opacity (Atreya *et al.* 1999, dePater *et al.* 2001). It is also useful in interpreting 20-cm wavelength maps of the outer planets made with the NRAO/VLA (Very Large Array). The next two, 2.25 GHz and 8.5 GHz correspond to the S-Band and X-Band radio transmission frequencies from both the Voyager and Cassini spacecraft, and results are now being used in the interpretation of absorption measured by radio occultation experiments at Neptune and Saturn (Hoffman *et al.* 2001). The 13.3 GHz measurement is conducted at a frequency which is close to the 13.78 GHz operating frequency of the Cassini RADAR experiment, which will operate in a passive mode to make high spatial resolution maps of the 2.2 cm emission from Saturn. Both the 13.3 GHz and 21.7 GHz measurements are close to the observing frequencies of the NRAO/VLA (Very Large Array), which has been used to image all of the giant planets. Thus, more accurate interpretation of those maps (using radiative transfer models such as ours) will be facilitated. Additionally, we pressed the system to operate at its highest possible frequency (approximately 27 GHz) to make measurements of phosphine's opacity nearer to the new, Ka-Band frequency (32 GHz), to be used as part of the Cassini radioscientific studies, although our centimeter-wavelength system sensitivity is relatively poor at that frequency.

Initial measurements were conducted at room temperature, both in order to better test the system, and because 300 K corresponds closely to the temperature in the deep atmosphere of Jupiter at which the Galileo probe detected large 21 cm opacity. The results from the first set of measurements were so striking, that they were quickly published as a note in the July 1999 issue of *ICARUS* (Hoffman *et al.*, 1999), and were presented at the 1998 DPS/AAS meeting (Hoffman *et al.*, 1998) and at the 1999 National Radio Science Meeting in a special session on solar system research (Hoffman and Steffes, 1999a). First results for the colder temperatures characteristic of the outer planets were presented at the 1999 DPS/AAS meeting (Hoffman and Steffes, 1999b). By the end of CY2000, a large number of additional measurements were completed over a wide range of temperatures, pressures and frequencies, and a formalism for computing the centimeter-wavelength opacity of phosphine for conditions characteristic of the outer planets was developed. These were first presented at the 2000 DPS/AAS Meeting (Hoffman and Steffes, 2000), and then presented by Hoffman at the student paper competition of the National Radio Science Meeting (Hoffman and Steffes, 2001 – James Hoffman won first place!) and is currently in press for the journal *ICARUS* (Hoffman *et al.*, 2001). Note that the *ICARUS* paper now in press also won for James Hoffman the SAIC/Georgia Tech best Ph.D. student paper award.

As discussed in the appended papers, the major discovery of this work has been that the centimeter-wavelength opacity of phosphine is more than an order of magnitude greater than that predicted from theory. This higher-than-expected opacity is due to an underestimation of the strength of the collisionally-induced rotational lines of phosphine, whose intensities have never been measured. These results have far-reaching implications in that they fundamentally change the interpretation of the Voyager radio occultation data obtained at Saturn and Neptune. Likewise, they will fundamentally change the expected results and the approaches to interpreting data from the Cassini three-frequency radio occultation studies at Saturn, as well as from the high spatial resolution 2.2 cm-wavelength radiometric maps of Saturn to be obtained from the Cassini RADAR experiment. Our results have already been provided to the Cassini Radioscience Team (A.J. Kliore, E. Marouf, J.M. Jenkins, *et al.*) and to the members of the Cassini RADAR experiment team involved with passive radiometric sensing of Saturn's atmosphere (M.A. Janssen, S.J. Bolton, M.J. Klein, and S. Gulkis). We have also provided the results to various planetary radio astronomers (e.g., I. dePater, D. Dunn, B. Butler, etc.) for use in their planning of future observations of the outer planets.

C. Existing and Proposed Applications to Observations and Radiative Transfer Modelling

As discussed in the appended paper by Hoffman *et al.* (2001, preprint attached as Appendix B), a new formalism for the *microwave* (i.e. $f < 30$ GHz) opacity of phosphine under conditions for the outer planets has now been developed. These results have been applied to the interpretation of existing results from the Voyager radio occultation measurements at Saturn and Neptune, as well as to the results from the Galileo-Jupiter entry probe radio opacity measurements, in order to determine the role of PH_3 in the

microwave opacity of those atmospheres, and to determine its deep atmospheric abundance. In the appended paper, the formalism is also applied to our *disk-averaged* radiative transfer model for Neptune (from DeBoer and Steffes, 1996a), and an estimate of PH_3 abundance (approximately 4x solar) has been derived which is consistent with the measured Neptune microwave (1.3 – 20 cm) emission data, and radio occultation results. In the same paper we also apply our formalism for phosphine opacity to our *disk-averaged* radiative transfer model for Saturn (DeBoer, 1995). An estimate of PH_3 abundance (approximately 10x-20x solar) and NH_3 abundance (approximately 2.5 solar) has been derived which is consistent with the measured Saturn microwave (1.3 – 20 cm) emission data, and radio occultation results.

At this writing (May 2001) we have just completed development of a *localized* radiative transfer model for the atmosphere of Saturn using our new formalism for phosphine opacity (Hoffman, 2001). This model uses ray-tracing to determine the microwave emission at specific localities on the disk of Saturn, which will be used in interpreting the moderate spatial resolution maps which have been obtained using the VLA (Very Large Array). (See, for example, dePater and Massie, 1985, Grossman *et al.*, 1989, Briggs and Sackett, 1989, or Dunn, 1999.) This radiative transfer model will also be useful in determining the sensitivity of the high spatial resolution 2.2 cm wavelength maps which will be obtained from the Cassini RADAR experiment to both phosphine abundance and ammonia abundance in Saturn's atmosphere. Among other activities in the first year (CY02) of the proposed three year program (02-04), we will apply this model to existing microwave maps of Saturn obtained from the VLA. This has the potential to set limits on spatial variations in the abundances of *both* phosphine and ammonia. Likewise, we will provide the members of the Cassini RADAR experiment team with sensitivity estimates for their instrument to both PH_3 and NH_3 , which will aid them in determining the most productive "look-angles" they should select when scanning across the disk of Saturn.

D. Proposed Laboratory Measurements

1. Measurements of the Opacity of PH_3 and NH_3 at Wavelengths from 7.3 to 9.3 mm

As can be seen from our results presented in Hoffman *et al.* (2001, preprint attached as Appendix B), the accuracy of our centimeter-wave measurement system degrades significantly at wavelengths shortward of 1.3 cm. While the system is able to reliably detect the 27 GHz (1.1 cm) opacity of the mixture containing 8.2% PH_3 at the highest pressure measured (5 Bars), the percentage uncertainty at lower pressures is quite large. This is not surprising in that the sensitivity of the cylindrical resonators is significantly reduced at higher frequencies. There are however, several compelling reasons requiring precise knowledge of the *millimeter* wavelength opacity from PH_3 under conditions characteristic of the Jovian planets.

The first and most compelling motivation is phosphine's role in the upper troposphere of Saturn. Unlike many other sensible constituents (such as ammonia), phosphine never condenses in Saturn's atmosphere. This is due to its extraordinarily high saturation vapor

pressure (Orton and Kaminski, 1989). As a result, *variations* in phosphine's abundance in the Saturn's upper troposphere are due most likely to photodissociation, while its *absolute* abundance is related to the eddy diffusion coefficient, which drives mixing in the upper troposphere (See, for example, Fegley and Lodders, 1994, or Orton *et al.*, 2000). While detection of PH_3 in the upper troposphere of Saturn has been made by Weissstein and Serabyn (1994, 1996) at two different wavelengths (1.1 mm and 0.37 mm), the limited signal-to-noise ratio and the limited vertical resolution of such measurements make it difficult to tightly constrain PH_3 abundance profiles, and the resultant eddy diffusion coefficient. Shorter wavelength measurements already obtained from ISO (the Infrared Space Observatory) and from the upcoming Cassini mission will provide some additional data on upper tropospheric phosphine abundance, once new laboratory work is completed (L. Brown, JPL, personal communications), but will still have limited vertical resolution.

The highest vertical-resolution profiles of PH_3 in the upper troposphere of Saturn will actually be obtained using the new 32 GHz (9.3 mm) transmitter included in the Cassini radioscience system. While 13-cm and 3.6-cm radio occultation experiments from Voyager were only able to detect phosphine at pressures greater than about 0.8 Bars (see Hoffman *et al.*, 2001, preprint attached as Appendix B), the increased opacity and higher spatial resolution obtainable at 9.3 mm will make detection of phosphine abundance profiles possible up to altitudes with pressures as low as 300 milliBars, and with vertical resolution on the order of 2 km. As shown in Figure 1 (from Hoffman, 2001), the effect of PH_3 is clearly discernable in the predicted 9.3 mm absorption profile over the 0.3 – 0.8 Bar pressure range. Since the accuracy of the derived PH_3 profiles will depend completely on the accuracy of the expressions for 9.3-mm PH_3 opacity, we are currently renovating our laboratory measurement system, so as to measure the *millimeter* wavelength refraction and absorption from PH_3 , using the Fabry-Perot resonators we previously used in our studies of ammonia (Joiner *et al.*, 1989 and Joiner and Steffes, 1991).

As shown in Figure 2, the system is being reconfigured with a Fabry-Perot resonator operating in the 32-41 GHz range (7.3-9.3 mm wavelengths), which corresponds closely to the frequency of the new "Ka-Band" (32 GHz) radio occultation measurement which will be conducted from the Cassini orbiter at Saturn, and to the operating frequency of the new "Q-Band" receivers at the Very Large Array (VLA) (43 GHz) which have recently been used to image Saturn (Dunn, 1999). In our work of a decade ago (Joiner *et al.*, 1989), our system only achieved sensitivities on the order of 40 dB/km (or 9.2 km^{-1} minimum detectable opacity) which would be well above the opacity expected from the $\text{H}_2/\text{He}/\text{PH}_3$ mixtures we have used in our measurements to date. However, by using our computer-based microwave measurement system (DeBoer and Steffes, 1996b) and the computer-controlled HP-8564E spectrum analyzer and HP-83650B microwave sweep generator, which were purchased by Georgia Tech for this project in 1998, we can now achieve sensitivities on the order of 3 dB/km (or 0.7 km^{-1}) which would readily allow measurement of the expected opacities (4-20 dB/km) from the phosphine gas mixture at the temperatures, pressures, and frequencies described below.

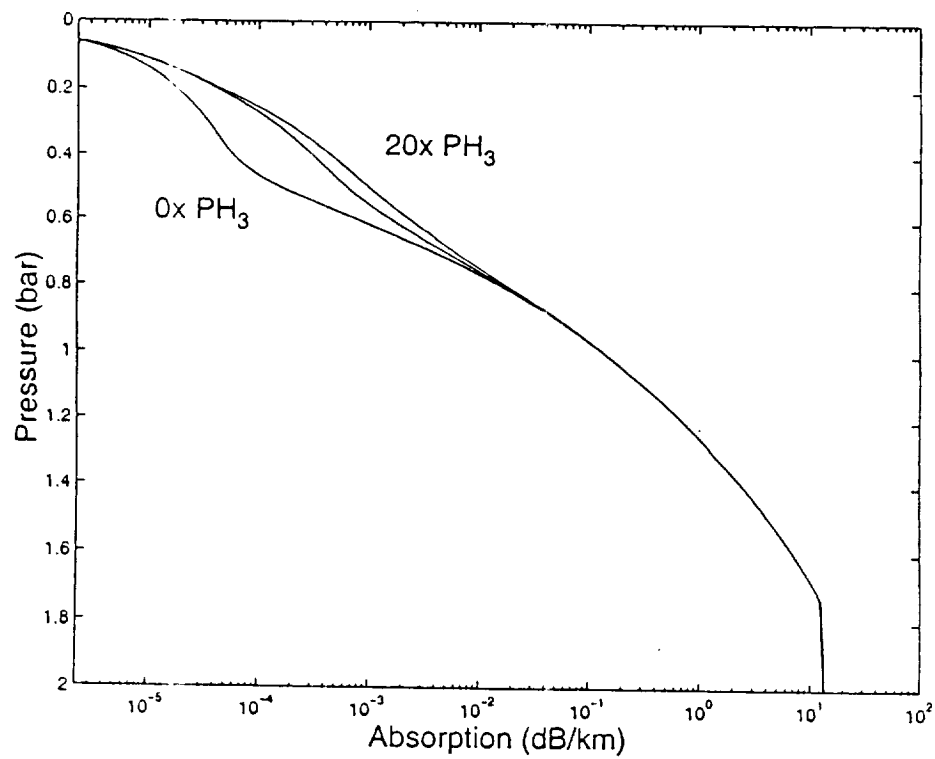


Figure 1: Predicted 9.3 mm (32 GHz) vertical opacity profile of a Saturnian atmosphere dominated by a saturation abundance of ammonia and phosphine. The vertical mixing ratio profile of phosphine follows that of the Orton *et al.* (2000) detections, with a deep mixing ratio of 0, 10 and 20-solar. (From Hoffman, 2001)

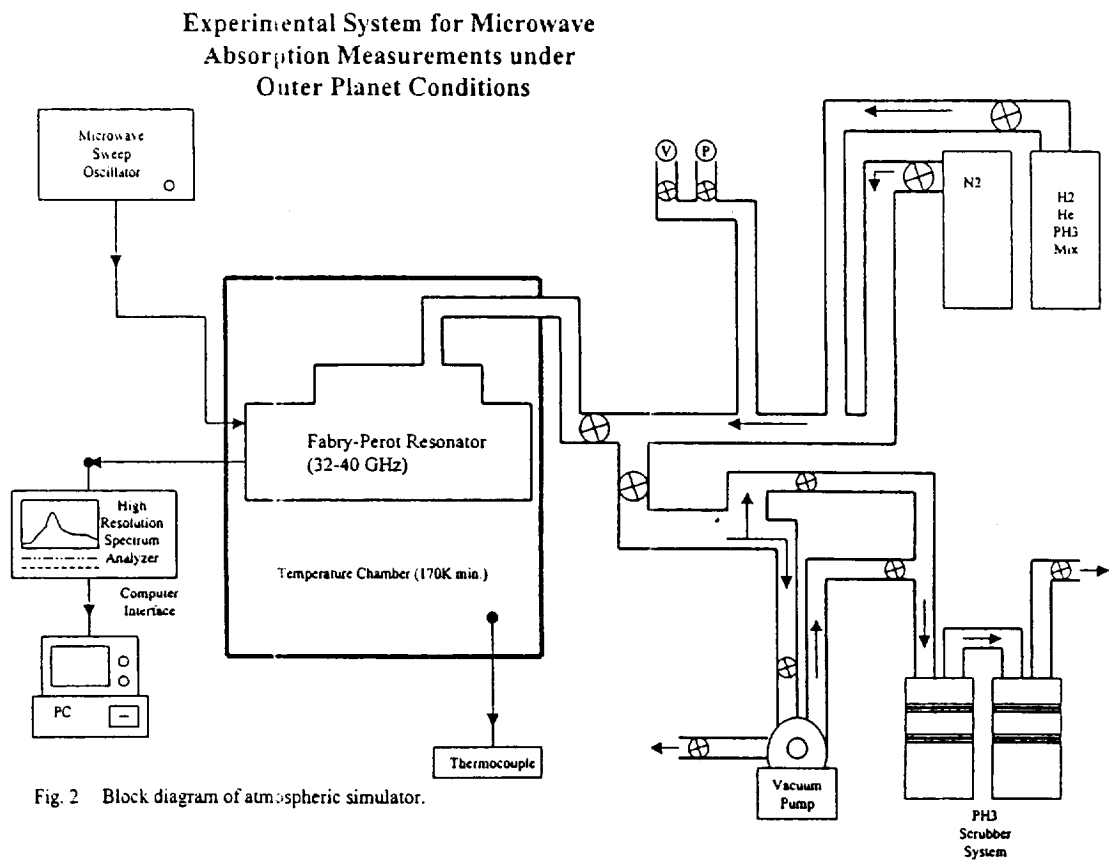


Fig. 2 Block diagram of atmospheric simulator.

In the first year of the new grant cycle (January 1, 2002-December 31, 2002) the opacity and refractivity of a custom-manufactured (Matheson) gaseous mixture consisting of 82.6% H_2 , 9.2% He, and 8.2% PH_3 will be measured at 4 frequencies between 32 and 41 GHz (wavelengths from 7.3-9.3 mm). Pressures from 0.5 to 2 Bars will be used, since these correspond to the pressure range in Saturn's atmosphere where both 32 GHz radio occultation measurements and 43 GHz radio emission measurements are most sensitive to phosphine (ref. Hoffman, 2001 and DeBoer, 1995, respectively). While initial measurements will be conducted at room temperature, in order to better test the system, the same measurements will be repeated at 210 K and at 170 K (the coldest temperature at which our system can be run), so as to characterize the temperature dependence of phosphine's opacity in an H_2 /He atmosphere under conditions similar to the upper troposphere of Saturn. It should be noted that in this pressure regime, the absorption being measured still resembles a continuum, with contributions from dozens of collisionally-induced rotational lines.

Since the 32-41 GHz system to be used is nearly an order of magnitude more sensitive than the system we used a decade ago, we will also repeat a number of the measurements of the opacity from a 2 % mixture of *ammonia* (NH_3) in a H_2 /He atmosphere originally conducted by Joiner *et al.* (1989). The new measurements, however, will be under the same temperature and pressure conditions as described above for phosphine, so as to more tightly constrain the model for *ammonia* opacity which is also used in interpreting the 32 GHz radio occultation measurements and 43 GHz radio emission measurements. This is especially important since the two most recent models for centimeter-wave and millimeter-wave opacity from ammonia under Jovian conditions (Joiner and Steffes, 1991 and Spilker 1993) use Ben-Reuven lineshapes tailored to fit the laboratory measurements from Joiner *et al.* (1989), which were all made at a pressure of 2 Bars. However, theory predicts that there should be a smooth transition from the Ben-Reuven lineshape to the Van Vleck-Weisskopf lineshape at some lower, but yet undetermined pressure (Joiner, 1991). Since that pressure may well lie in the 0.3-0.8 Bar range sensed by both Ka-Band (32 GHz) radio occultation measurements and Q-Band (43 GHz) radio astronomical observations, additional measurements to better constrain the opacity from ammonia under those conditions will be crucial.

It should also be noted that the pressure vessel surrounding our Ka-Band Fabry-Perot resonator is made of Pyrex glass, so that *adsorption* of PH_3 into the pressure vessel walls will not be nearly as pronounced as it was with the stainless steel pressure vessel used in our centimeter-wavelength system. (Note however, that the amount of PH_3 adsorbed from the gas mixture with the centimeter-wave system was less than 250 ppm when using a gas mixture containing 8% PH_3 , even with pressures as high as 6 Bars.) As a precaution however, the measurements of the gas mixture containing phosphine will be conducted first, since its long millimeter-wavelength opacity (32-41 GHz) will be significantly less than that from ammonia, and thus contamination caused by any opacity from adsorbed ammonia will be avoided.

2. Measurements of the Opacity of PH_3 and NH_3 at 3.2 mm

In the second year of the new grant cycle (January 1, 2003 – December 31, 2003), the opacity and refractivity of the same custom-manufactured (Matheson) gaseous mixture consisting of 82.6% H_2 , 9.2% He , and 8.2% PH_3 will be measured at 94 GHz (3.2 mm wavelength), since this wavelength has been recently used for interferometric mapping of Saturn using the Berkeley-Illinois-Maryland Association (BIMA) array (see, e.g., van der Tak *et al.*, 1999). In the future, the high spatial resolution maps of the outer planets derived from the combination of the BIMA and CalTech millimeter-wavelength arrays, and development of the NRAO/ALMA (Atacama Large Millimeter Array) will make accurate knowledge of phosphine's opacity at this wavelength even more compelling. Likewise, precision measurement of the emission spectra of the outer planets obtainable at this wavelength with the new NRAO 100-meter antenna (the GreenBank Telescope, or GBT) can only be accurately interpreted with accurate knowledge of the microwave absorption properties of phosphine. As with the 32-41 GHz measurements, pressures from 0.5 to 2 Bars will be used, since these correspond to the pressure ranges in the atmospheres of the outer planets where ~ 90 GHz radio emission measurements are most sensitive to phosphine. Measurements will be conducted at 295K, 210 K, and at 170 K (the coldest temperature at which our system can be run), so as to characterize the temperature dependence of phosphine's opacity in an H_2/He atmosphere under conditions similar to the upper tropospheres of the outer planets.

In order to conduct measurements at the 3.2 mm wavelength, a different Fabry-Perot resonator will be used, one which had previously been used to characterize the 3.2 mm wavelength properties of NH_3 under Jovian conditions (Joiner and Steffes, 1991) and of SO_2 under simulated Venus conditions (Fahd and Steffes, 1992). (See Figure 3.) However, as with the lower frequency system, we can now achieve substantially better sensitivities than a decade ago. Due to improved microwave instrumentation and the computer-based measurement system, the sensitivity has been improved by an order of magnitude (from 30 dB/km to 3 dB/km). Since the 94 GHz system to be used is an order of magnitude more sensitive than the system we used a decade ago, we will also repeat the measurements of the opacity from NH_3 in a H_2/He atmosphere conducted by Joiner and Steffes (1991), under the same temperature and pressure conditions as described above for phosphine, so as to more tightly constrain the model for ammonia opacity also used in interpreting the 3.2 mm radio emission measurements of the outer planets.

The results of both sets of measurements will then be applied to the new *localized* radiative transfer model described above (Section II.C) in order to better interpret maps of Saturn's emission at this wavelength (e.g., van der Tak, *et al.*, 1999), and to infer potential spatial variations in the abundances of phosphine and ammonia in the atmosphere of Saturn.

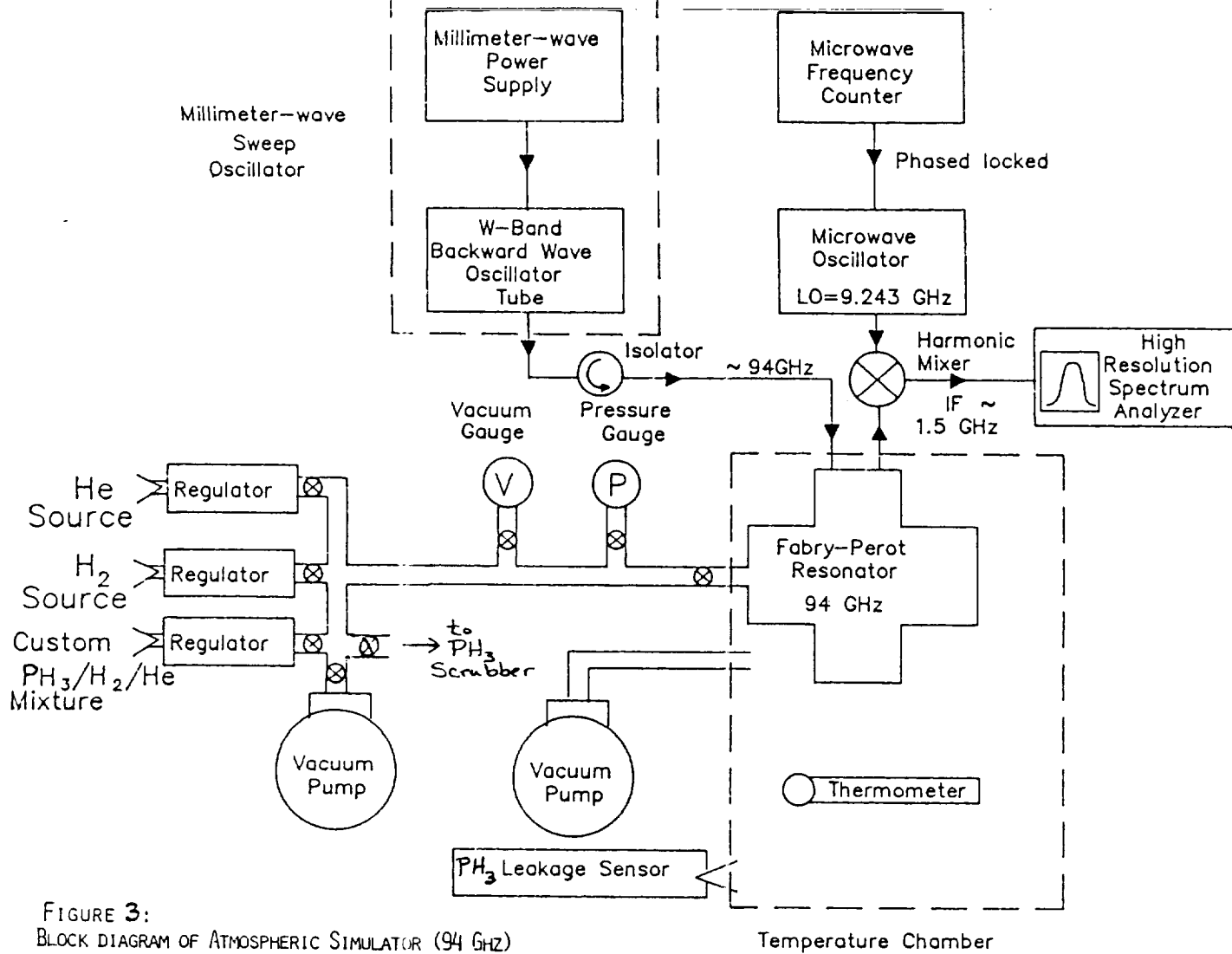
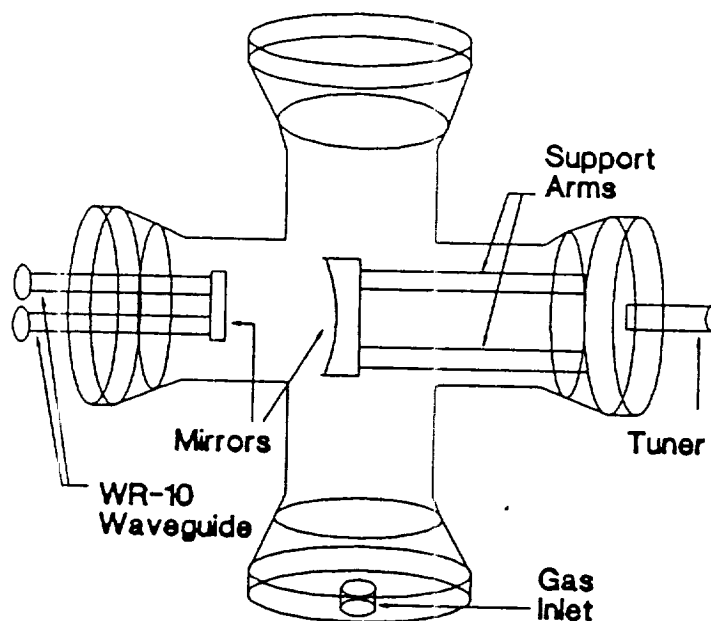


FIGURE 3:
BLOCK DIAGRAM OF ATMOSPHERIC SIMULATOR (94 GHz)



Sketch of the W-band Fabry-Perot resonator (94 GHz)

3. Measurements of the Opacity of NH_3 and PH_3 at 1.5 mm

Over the past decade, a number of observations the Jupiter and Saturn have been undertaken in the millimeter, sub-millimeter, and far infrared spectral range. The development of instruments such as the Cal Tech Submillimeter-Wave Fourier Transform Spectrometer (deployed on Mauna Kea) has made it possible to measure continuous spectra from 120 GHz to 1 THz ($4\text{--}33.3\text{ cm}^{-1}$), except for those spectral regions obscured by the earth's atmosphere (see, e.g., Weisstein and Serabyn, 1996). One recent problem which has been identified in such measured spectra is that the peak in emission, which was predicted to occur at a frequency below that for the minimum in the ammonia opacity (205 GHz), has actually been measured to occur at higher frequencies (Orton, personal communications). This may be the result of errors in the model for the ammonia opacity attributable to its longer wavelength ammonia inversion lines (near 24 GHz), or may be due to errors in models for the continuum absorption due to ammonia's lowest rotational lines (572, 1168, and 1215 GHz). It may also be due to errors in the models for opacity due to phosphine which have been used. Thus, in the third year of the new grant cycle (CY 2004), we will conduct measurements of the opacity from both PH_3 and NH_3 in an H_2/He atmosphere at 200 GHz (1.5 mm) in an attempt to resolve this inconsistency. These measurements would be conducted at the same temperatures, pressures and mixing ratios used for the 3.2 mm measurements (described above in Section II.D.3), but would use a klystron tube signal source, such as was used in our previous 1.4 mm-wavelength laboratory measurements of H_2S in an H_2/He atmosphere (Joiner *et al.*, 1992). These measurements would also utilize yet a third ultra-sensitive Fabry-Perot resonator (Valkenburg and Derr, 1966) which is now in our laboratory. (Note that during the third year of the proposed grant, these measurements will be conducted *in addition* to the measurements of HCl under Venus conditions described below.)

III. VENUS STUDIES

A. Recent Results

In this last year of our current grant cycle (1/1/01-12/31/01), we have continued our interpretative studies of the Venus microwave radio emission maps taken by our students in 1996 and of Magellan radio occultation studies, working with the other investigator groups (both IR and microwave), so as to yield the best possible understanding of the variations in constituent abundances and the atmospheric dynamics on a global basis. After completion of our laboratory-based formalisms for the opacity of SO_2 (Suleiman *et al.*, 1996) and gaseous H_2SO_4 (Kolodner and Steffes, 1998) under Venus atmospheric conditions, new interpretative studies of both Venus radio occultation absorptivity profiles and Venus microwave radio emission maps were undertaken and have now been completed. A paper using our laboratory results and 1996 observations of Venus with the VLA (Very Large Array) to interpret the *disk-averaged* emission from Venus, was jointly authored with Bryan Butler (NRAO/Socorro) and Jon Jenkins (SETI Institute/NASA Ames) and will appear in ICARUS this year (Butler *et al.*, 2001). An accompanying

paper on interpretation of high-resolution radio maps of Venus developed from our 1996 Venus observations was also submitted with the same co-authors (Jenkins *et al.*, 2001) giving unique insights into the distribution and spatial variation of the abundances of $\text{H}_2\text{SO}_4(\text{g})$ and into the variability of the atmospheric temperature structure.

One troubling aspect of the observed spectrum of the disk-averaged microwave emission from Venus has to do with the brightness at the 3.6 cm wavelength (8.4 GHz). Both in our most recent work (Butler *et al.*, 2001, abstract attached as Appendix C) and in our previous work (Steffes *et al.*, 1990 and Suleiman, 1997), the disk-averaged abundances of gaseous H_2SO_4 (approximately 2.5-5 ppm in a relatively thin layer [~ 5 -10 km] below the base of the main cloud) and SO_2 (approximately 40-90 ppm below the base of the main cloud), which are required to match the emission spectrum at wavelengths *shortward* of 3 cm, result in modeled brightness temperatures at 3.6 cm that are well below, or just barely consistent with the lower limit of, the observed 3.6 cm brightness. For example, in Figure 4 (from Butler *et al.*, 2001), the modeled Venus emission agrees well with all measured data except that at 3.6 cm. A marginal fit can be achieved using the model, but only if the minimum possible (and less likely) abundances of SO_2 (40 ppm) and gaseous H_2SO_4 (2.5 ppm) consistent with other independent measurement techniques are assumed.

Since the disk-averaged 3.6 cm brightness temperatures determined by measurements made from the NASA/DSN Goldstone 64-meter Antenna (652 K, Steffes *et al.*, 1990) and by measurements made using the NRAO/VLA (657 K, Butler *et al.*, 2001) were essentially identical, the only systematic source of error in both *measurements* would be the flux scale (or reference radio source intensity) against which both radio telescopes were calibrated. Working with Bryan Butler and Rick Perley at NRAO/Socorro and Michael Klein at JPL, we carefully reviewed all radiometric flux scale calibrations at this wavelength, and concluded that the stated accuracy of $\pm 2\%$ was indeed correct. Thus, the variation from the modeled 3.6 cm brightness temperatures ranging from 612 K (Suleiman, 1997) up to 640 K (Butler *et al.*, 2001) is significant. In order to check for errors in the models of Venus microwave emission, the current models for the microwave opacity of known microwave absorbing constituents, including CO_2 , N_2 , SO_2 , H_2SO_4 (gaseous and liquid), OCS, H_2O , and CO were conducted with Brian Butler (NRAO) and Jon Jenkins (SETI Institute/NASA Ames RC), and all were concluded to be accurate to within their stated uncertainties. Thus it was concluded that some other source of increased emission must be present.

Great insight into the nature of the microwave emission from the Venus can be gained by inspecting the “weighting functions” for the different wavelengths. In Figure 5 (from Suleiman, 1997), the relative contributions to the microwave emission from different layers of the atmosphere (or “weighting functions”) are shown. At 8.4 GHz (3.6 cm wavelength) most emission originates from the surface, with a smaller, but significant contribution from the lowest layers of the atmosphere (0-20 km altitude). While the physical temperature of the Venus surface is approximately 735 K, the limited surface emissivity produces an equivalent disk-averaged brightness of only about 638 K.

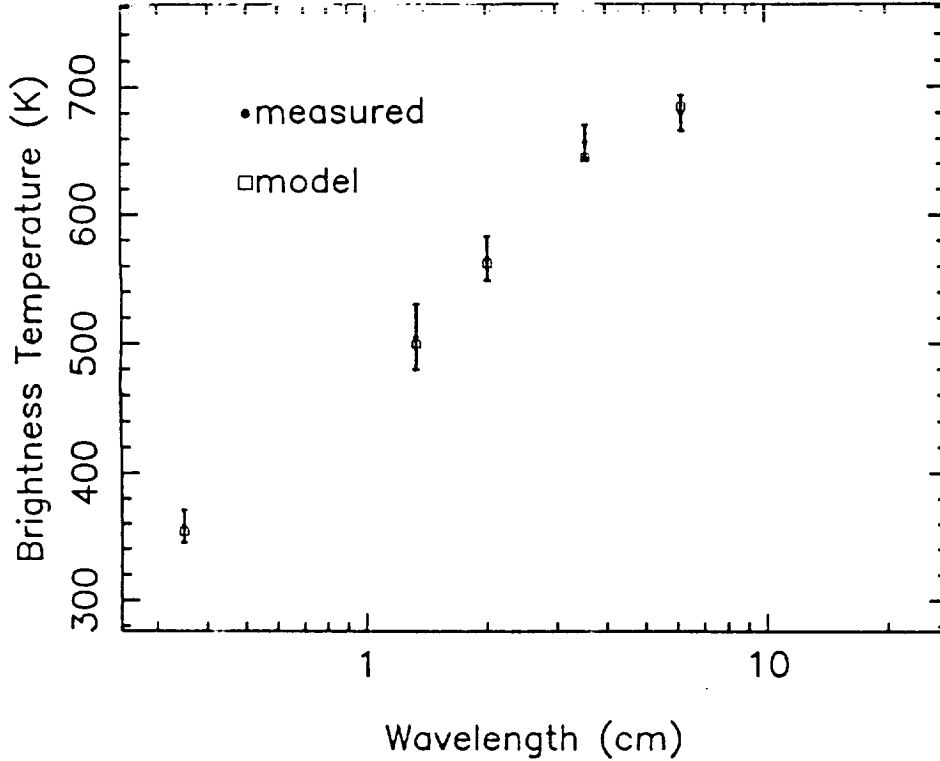


Figure 4: Disk averaged brightness temperatures for Venus at 5 wavelengths compared with modeled values. (From Butler et al., 2001)

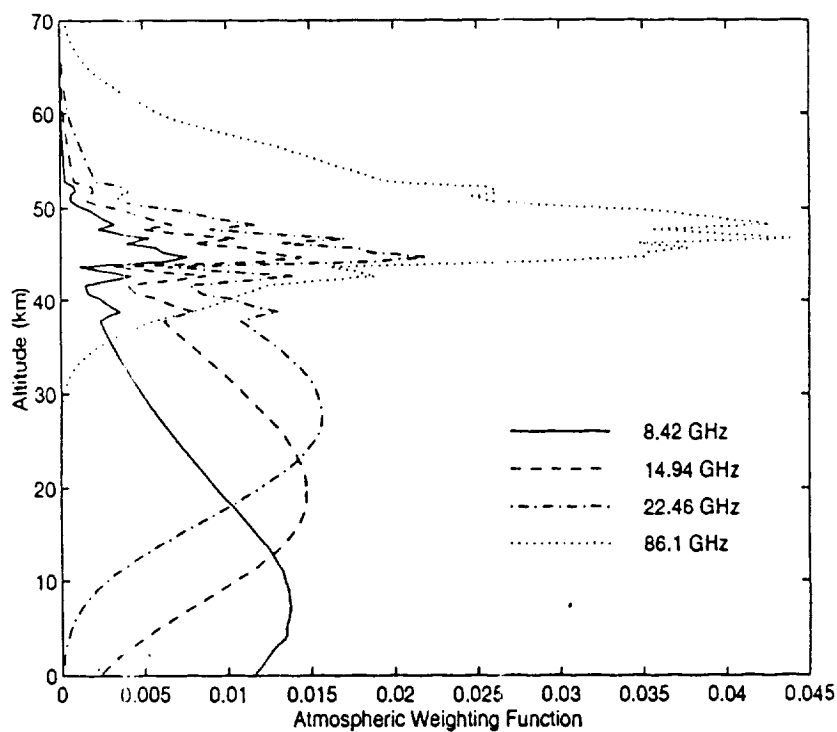


Figure 5: Disk-averaged atmospheric weighting functions of the Venus atmosphere as a function of altitude at frequencies of 8.42, 14.94, 22.46, and 86.1 GHz. The constituents of the Venus atmosphere used in the model are CO_2 , N_2 , H_2SO_4 , H_2O , CO , OCS , and SO_2 , where uniform abundance of 75 ppm below 48 km is used for SO_2 .

(Pettengill 1988). Thus, in order to raise the emission, a source of microwave opacity in the altitude ranges with physical temperatures above 638 K (0-13 km, as per Seiff *et al.*, 1980) is required. Moreover, this same source of opacity must itself be depleted, or its microwave opacity be reduced, in higher altitude ranges, so as to maintain the good fits obtained with the model-consistent abundances of gaseous H_2SO_4 and SO_2 at the shorter wavelengths. The recent detection (in the near-IR) of gaseous HCl in the deep atmosphere of Venus (Dalton *et al.*, 2000) provides a likely candidate for such opacity.

While HCl is not usually a strong absorber at centimeter-wavelengths, it does have extraordinarily strong sub-millimeter wavelength rotational lines at 625 GHz (30.3 cm^{-1}) and 1.25 THz (41.7 cm^{-1}) (JPL Catalog -- Poynter and Pickett, 1985). Thus, by using the published line intensities, and by assuming a VanVleck-Weiskopf lineshape, we have coarsely estimated the opacity of HCl in a CO_2 atmosphere at centimeter wavelengths, assuming the same line broadening parameter we measured for SO_2 in a CO_2 atmosphere (Suleiman *et al.*, 1996). Of special interest is that for abundances of 100 ppm or less, HCl has no significant effect on the centimeter wavelength opacity in the pressure (altitude) ranges sensed by radio occultation experiments (see, e.g., Steffes *et al.*, 1994) and only a small effect in the pressure (altitude) ranges sensed by microwave radio emission measurements (see Figure 5), EXCEPT at 3.6 cm (8.4 GHz). At 3.6 cm, a 100 ppm abundance of HCl would increase the opacity in the highest pressure (deepest altitude) ranges by nearly 10%, increasing the modeled 3.6 cm brightness by nearly 10 K. Since a 10 K signal is readily measurable with a system such as the VLA, it may in fact be possible to use maps of the 3.6 cm brightness which can be derived from existing data already archived at the NRAO/VLA (Butler, private communication) to map variations in the low-altitude abundance of HCl, providing a much better understanding of the dynamics of the boundary layer in the deep atmosphere. It should be noted that while the HCl abundance derived by Dalton *et al.* (2000) was only on the order of 1 ppm, the current coarse estimates of the microwave opacity of HCl are likely accurate to no better than one or two orders of magnitude, especially under Venus atmospheric conditions. Thus, the accuracy of any retrieved abundances will depend completely on the accuracy of the expressions for the 8.4 GHz (3.6 cm) opacity of HCl, which depend on pressure, temperature, and mixing ratio.

B. Proposed Laboratory Measurements

Since the accuracy of the HCl abundance in the deep Venus atmosphere derived from 3.6 cm emission maps will depend completely on the accuracy of the expressions for 3.6 cm HCl opacity, we will conduct measurements of the centimeter-wavelength properties of HCl in the third year of the new grant cycle (January 1, 2004 – December 31, 2004). As shown in Figure 6, we will use our centimeter-wavelength system configured as when Kolodner and Steffes (1998) used it to measure the opacity of gaseous H_2SO_4 under simulated Venus conditions, except replacing the sulfuric acid with hydrochloric acid. As in our previous work with sulfuric acid, the resonators will be re-plated with gold, so as to prevent reactions with the acid vapors. Liquid hydrochloric acid will be vaporized and then mixed with CO_2 , so as to characterize its microwave absorption and refraction under

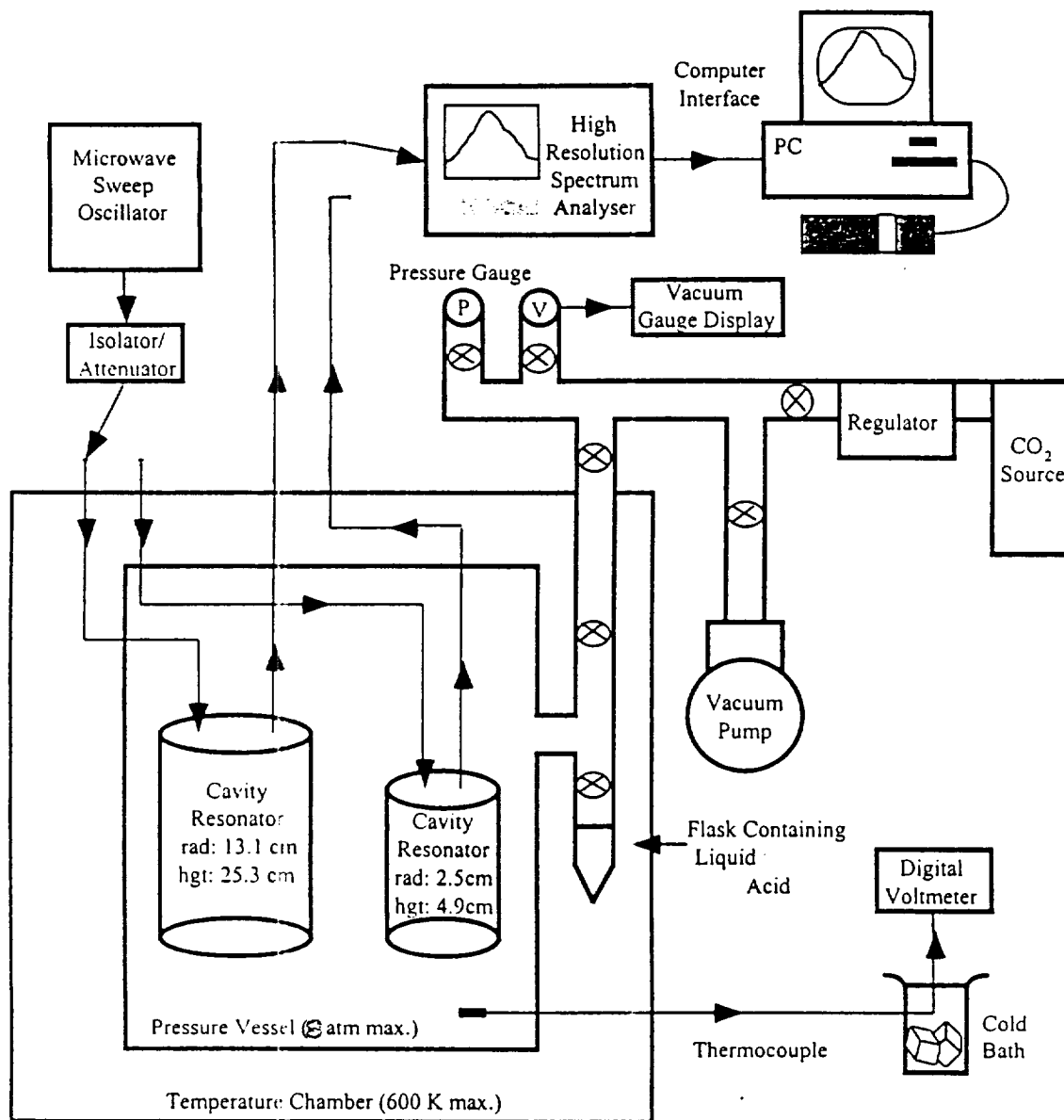


Figure 6: Block diagram of the centimeter-wave system configured for measurement of the microwave absorption of gaseous hydrochloric acid under simulated Venus conditions.

Venus conditions. Measurements will be conducted at three frequencies (wavelengths): 8.3 GHz (3.6 cm), 13.3 GHz (2.3 cm), and 21.7 GHz (1.38 cm), which are near the three NRAO/VLA operating frequencies used for sensing of the Venus atmosphere. A mixture consisting of 99% CO₂ and 1% gaseous HCl will be used, with temperatures ranging from 300-600 K, and with pressures up to 8 Bars. While this pressure doesn't approach the 92 Bars characteristic of the Venus surface, it will be high enough so that the centimeter wavelength continuum should be well detectable. Likewise, the pressure and temperature dependencies of the opacity can be readily measured. As with our previous work, our goal will be to develop a measurement-based formalism for the opacity of HCl in a CO₂ atmosphere and then apply that formalism to our radiative transfer model for the Venus atmosphere so as to retrieve HCl abundances from radio emission measurements.

IV. PROPOSED PROCEDURE AND LEVEL OF EFFORT

The proposed level of effort for the scientific research in the three year period proposed (January 1, 2002 through December 31, 2004) involves one professor (P.G. Steffes, Professor of Electrical and Computer Engineering) at 25% time, and one graduate student (Graduate Research Assistant, Priscilla N. Mohammed) at 50% time, with supplies and other support as indicated in the attached cost breakdown. (See pp 24-28.) (Note that 50% is the maximum support level for Ph.D. students, with the remaining 50% considered as registered academic thesis research.) GRA Priscilla Mohammed joined this project a year ago, being supported in her first year by a new graduate student fellowship at Georgia Tech, and has assumed this Graduate Research Assistant position opened by the graduation of Dr. James Hoffman. In addition to the participation in the program by Professor Steffes and the paid graduate research assistant, contributions to the program from both graduate and undergraduate students working on special projects for academic credit have been substantial. Likewise, in the spirit of the NASA Graduate Student Researchers Program, and in conjunction with Georgia Space Grant Consortium, we continue to seek out talented underrepresented minority students and involve them in our program.

The amount of collaborative work we have conducted in both our Venus atmospheric studies and in our studies of the outer planets has demonstrated a need for a reference source of information regarding the microwave and millimeter-wave absorption properties of planetary atmospheres. At the suggestion of Dr. Reta Beebe (NMSU) who is responsible for the Planetary Atmospheres node of the Planetary Data System (PDS), we have created a web page which allows direct access to references of laboratory results for the microwave and millimeter-wave absorptive and refractive properties of planetary atmospheric constituents, both from our group and from others in the world. The URL for this page is <http://users.ece.gatech.edu:80/~psteffes/palpapers/planetar.htm>. This page currently lists only references to published papers, but will be improved to allow access to expressions and even downloadable routines for computing microwave absorption properties. This page is linked to be accessible from the PDS web pages.

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- Suleiman, S. H., M. A. Kolodner, and P. G. Steffes 1996. Laboratory measurement of the temperature dependence of gaseous sulfur dioxide (SO₂) microwave absorption with application to the Venus atmosphere. *Journal of Geophysical Research (Planets)* **101**, 4623-4635.
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- Weisstein, E.W. and E. Serabyn 1994. Detection of the 267 GHz J=1-0 rotational transition of PH₃ in Saturn with a new Fourier transform spectrometer. *Icarus* **109**, 367-371.
- Weisstein, E.W. and E. Serabyn 1996. Submillimeter line search in Jupiter and Saturn. *Icarus* **123**, 23-36.

VI. FACILITIES

The specific laboratory measurements described in this proposal will be conducted at the Planetary Atmospheres Laboratory and the accompanying Remote Sensing Laboratory, which are located within the School of Electrical and Computer Engineering at Georgia Tech. A description of the equipment being used for these measurements is given in Sections II.D and III.B of this proposal, and in the appended papers.

For support of the required data analysis and computing activities, a wide range of computing services for education, research, and administration is provided by the Georgia Tech Office of Information Technology. Numerous personal computers are also available to support this project.

VII. BIOGRAPHICAL SKETCH

PAUL G. STEFFES

PROFESSOR

SCHOOL OF ELECTRICAL AND COMPUTER ENGINEERING

GEORGIA INSTITUTE OF TECHNOLOGY

ATLANTA, GEORGIA 30332-0250

EDUCATION

S.B.	Electrical Engineering	1977	Massachusetts Institute of Technology
S.M.	Electrical Engineering	1977	Massachusetts Institute of Technology
Ph.D.	Electrical Engineering	1982	Stanford University

EMPLOYMENT HISTORY

---Massachusetts Institute of Technology, Research Laboratory of Electronics, Radio Astronomy and Remote Sensing Group: Graduate Research Assistant, 1976-1977

---Watkins-Johnson Company, Sensor Development, San Jose, California Member of the Technical Staff, 1977-1982.

---Stanford University, Electronics Laboratory, Center for Radar Astronomy, Stanford, California, Graduate Research Assistant, 1979-1982.

Georgia Institute of Technology, School of Electrical and Computer Engineering, Atlanta, Georgia

Assistant Professor	1982-1988
Associate Professor	1988-1994
Professor	1994-Present

RESEARCH EXPERIENCE SUMMARY (At Georgia Tech):

Principal Investigator of the National Science Foundation Grant, "Remote Sensing of Clouds Bearing Acid Rain." This research studied and designed a microwave/millimeter-wave system for remotely sensing the pH of acidic clouds (1982-1983). Principal Investigator of the NASA Planetary Atmospheres Program, "Laboratory Evaluation and Application of Microwave Absorption Properties Under Simulated Conditions for Planetary Atmospheres." This research includes study of the interaction between atmospheric constituents and electromagnetic waves, along with application of these studies to spacecraft and radio telescopic measurements of the microwave absorption in atmospheres of Venus and the outer planets (1984-2001). Principal Investigator of the GTE Spacenet Program, "Satellite Interference Locating System (SILS)." The

program involved location of uplink signals on the surface of the earth without disrupting regular satellite operations (1986-1990). Principal Investigator of the Emory University/Georgia Tech Biomedical Technology Research Center project, "Research in Development of a Non-Invasive Blood Glucose Monitoring Technique." This research involved the use of active infrared systems to determine glucose levels in the human eye and bloodstream (1988-1989), with subsequent support (1990-1991) from Lifescan, Inc. Principal Investigator of the NASA Pioneer Venus Guest Investigator Program, "Pioneer Venus Radio Occultation (ORO) Data Reduction: Profiles of 13 cm Absorptivity." This research inferred 13 cm wavelength absorptivity profiles using the Pioneer Venus Orbiter, and then used such profiles to characterize abundance profiles for gaseous H₂SO₄ in the Venus atmosphere (1988-1990). Principal Investigator/Team Member of NASA High Resolution Microwave Survey (HRMS). This research involved development and operation of the world's most sensitive receiving system used for a 1-10 GHz Sky Survey (1991-1994). Subsequent support has been provided by the SETI Institute (1994-2000). Developer of atmospheric radio occultation experiments conducted with the Magellan (Venus) Spacecraft (1991-1994). Director of the Ku Band Satellite Earth Station System. Responsible for development of a Ku-band uplink/downlink system for use in inter-university networks (1985-1995). Principal investigator in the NASA/ACTS Propagation Experiments Program (1994-1999). This research involved study of Ka-Band propagation effects.

Teaching Activities: Principal Professor for "Satellite Communications and Navigation Systems" (graduate course) and for "Electromagnetics Design" (undergraduate design experience), have also taught "Antennas," "Introduction to Radar," "Electromagnetics," "Electromagnetics Applications," "Signals and Systems," and "Survey of Remote Sensing."

HONORS AND AWARDS

Member, Eta Kappa Nu; Member, Sigma Xi; Senior Member, IEEE (Member of 6 IEEE Societies).

Recipient of the Metro Atlanta Young Engineer of the Year Award, presented by the Society of Professional Engineers, 1985.

Recipient of the Sigma Xi Young Faculty Research Award, 1988.

Associate Editor, Journal for Geophysical Research (JGR-Atmospheres), 1984-1989.

Elected to the Electromagnetics Academy, October 1990.

Recipient of the Sigma Xi Best Faculty Paper Award, 1991.

Recipient of the NASA Group Achievement Award, "For outstanding contribution to the design, development, and operation of the High Resolution Microwave Survey Project, and its successful inauguration," March 1993.

Recipient of the 1996 IEEE Judith A. Resnik Award, "For contributions to an understanding of the Venus atmosphere through innovative microwave measurements," January 1996.

Named to the Editor's list of distinguished reviewers for the journal ICARUS (International Journal of Solar System Exploration), ICARUS, v. 134, p185.

OTHER PROFESSIONAL AFFILIATIONS

Member, American Association for the Advancement of Science.

Member, American Astronomical Society, Division for Planetary Sciences.

Member, American Geophysical Union; Member, American Institute of Physics.

Member, American Society for Engineering Education.

Elected Member, International Union of Radio Scientists (URSI), Commission J (Radio Astronomy).

OTHER PROFESSIONAL ACTIVITIES

- Chairman, National Research Council (NAS/NAE) Committee on Radio Frequencies, 1998-2001. (Member, 1995-98)
- Member of the NASA Management and Operations Working Group for the Planetary Atmospheres Program (1986-1990).
- Proposal/Panel Reviewer for the NASA Planetary Astronomy Program, the NASA Planetary Atmospheres Program, the NASA Planetary Instrument Definition and Development Program, the NASA Planetary Data Analysis Programs, the NASA Exobiology Program, the NASA Discovery Program, the NASA Pluto-Kuiper Express Mission, the NASA Pluto-Kuiper Belt Mission, the NASA/ESA Rosetta Mission, the NASA Microgravity Biotechnology Program, and the NSF Comm. Research Program.
- Reviewer/Referee for *Icarus* (International Journal of Solar System Studies), *Journal of Geophysical Research*, *Radioscience*, *IEEE Microwave and Guided Wave Letters*, *IEEE Transactions on Geoscience and Remote Sensing*, *Science*, and for several textbooks in the area of electromagnetics.

SELECTED RECENT PUBLICATIONS IN THE SPACE SCIENCES AREA:

- D. R. DeBoer, and P.G. Steffes, "Laboratory Measurements of the Microwave Properties of H₂S under Simulated Jovian Conditions with an Application to Neptune", *Icarus*, Vol. 109, pp. 352-366, June 1994.
- P. G. Steffes, J. M. Jenkins, R. S. Austin, S. W. Asmar, D. T. Lyons, E. H. Seale, and G. L. Tyler, "Radio Occultation Studies of the Venus Atmosphere with the Magellan Spacecraft. 1. Experiment Description and Performance," *Icarus*, vol. 110, pg. 71-78, July 1994.
- J. M. Jenkins, P. G. Steffes, J. Twicken, D. P. Hinson, and G. L. Tyler, "Radio Occultation Studies of the Venus Atmosphere with the Magellan Spacecraft 2. Results from the October 1991 Experiment" *Icarus*, vol. 110, pg. 79-94, July 1994.
- D. R. DeBoer and P. G. Steffes, "The Georgia Tech High Sensitivity Microwave Measurement System," *Astrophysics and Space Science*, Vol. 236, pp111-124, February 1996.
- S. H. Suleiman, M. A. Kolodner, and P. G. Steffes, "Laboratory Measurement of the Temperature Dependence of Gaseous Sulfur Dioxide (SO₂) Microwave Absorption with Application to the Venus Atmosphere," *Journal of Geophysical Research*, Vol. 101, Number E2, pp. 4623-4635, February 1996.
- D. R. DeBoer and P. G. Steffes, "Estimates of the Tropospheric Vertical Structure of Neptune Based on Microwave Radiative Transfer Studies," *Icarus*, vol. 123, pp. 324-335, October 1996.
- M. S. Alouini, S. A. Borgsmiller, and P. G. Steffes, "Channel Characterization and Modeling for Ka-Band Very Small Aperture Terminals," *Proceedings of the IEEE*, vol. 85, pp. 981-997, June 1997.
- M. A. Kolodner and P.G. Steffes 1998. "The Microwave Absorption and Abundance of Sulfuric Acid Vapor in the Venus Atmosphere based on New Laboratory Measurements," *Icarus*, vol.132, pp. 151-169, March 1998.
- J. P. Hoffman, P.G. Steffes, and D.R. DeBoer, "Laboratory Measurements of Phosphine's Microwave Opacity: Implications for Planetary Radio Science," *Icarus*, vol. 140, pp. 235-238, July 1999.
- D.R. DeBoer and P. G. Steffes, "Performance and Uses of a Refurbished 30-m Former Satellite Communications Antenna: The Georgia Tech Woodbury Research Facility," *RadioScience*, vol. 34, pp. 991-1003, July-August 1999.
- J.P. Hoffman, P.G. Steffes, and D.R. DeBoer, "The Microwave Absorption and Abundance of Phosphine in the Atmospheres of Saturn and Neptune Based on New Laboratory Measurements." *Icarus*, vol. 152, pp.172-184, July 2001.
- B.J. Butler, P.G. Steffes, S.H. Suleiman, M.A. Kolodner and J.M. Jenkins, "Accurate and Consistent Microwave Observations of Venus and Their Implications." *Icarus*, vol. 154, pp. 226-238, December 2001
- J.M. Jenkins, M.A. Kolodner, B.J. Butler, S.H. Suleiman, and P.G. Steffes, "Microwave Remote Sensing of the Thermal Structure and the Distribution of Sulfur Compounds in the Venus Atmosphere." Submitted to *Icarus*, May 2001.

SELECTED RECENT CONFERENCE PRESENTATIONS WITH PUBLISHED PROCEEDINGS OR ABSTRACTS:

- S. H. Suleiman, M. A. Kolodner, B. J. Butler, and P. G. Steffes, "VLA Images of Venus at 1.3 cm and 2 cm Wavelengths," Bulletin of the American Astronomical Society, vol. 28, pg 1117. Presented at the 28th Annual Meeting of the Division for Planetary Sciences of the American Astronomical Society, Tucson, AZ, October 24, 1996.
- M. A. Kolodner, S. H. Suleiman, B. J. Butler, and P. G. Steffes. "The Abundance and Distribution of Sulfur-Bearing Compounds in the Lower Venus Atmospheres." EOS Trans. AGU 77, No. 46, Fall Meet. Suppl., p. F439. Presented at the Fall Meeting of the American Geophysical Union, San Francisco, CA, December 16, 1996.
- S. A. Borgsmiller and P. G. Steffes, "Measurements of Ka-Band Amplitude and Phase Scintillation", Proceedings of the Twenty-First NASA Propagation Experimenters Meeting (NAPEX XXI). Presented at the NASA Propagation Experimenters Meeting (NAPEX XXI). El Segundo, CA, June 12, 1997.
- M. A. Kolodner, S. H. Suleiman, B. J. Butler, and P. G. Steffes. "Latitudinal Variations of Sulfur Compounds in the Venus Atmosphere Based on the Correlation between VLA Observations and Radio Occultation Results." Bulletin of the American Astronomical Society 29, 1042-1043. Presented at the 29th Annual Meeting of the division for Planetary Sciences of the American Astronomical Society, Cambridge, MA, August 1, 1997.
- J.P. Hoffman, P. G. Steffes, and D. R. DeBoer, Preliminary Results of Laboratory Measurements of the Centimeter Wavelength Properties of Phosphine under Simulated Conditions for the Outer Planets, "Bulletin of the American Astronomical Society, vol. 30 no. 3, 1998. p. 1102. Presented at the 30th Annual Meeting of the Division for Planetary Sciences of the American Astronomical Society, Madison, WI, October 15, 1998
- B.J. Butler, J.M. Jenkins, and P.G. Steffes, "Whole-disk Microwave Brightness Temperature Spectrum of Venus," Bulletin of the American Astronomical Society, vol. 30, no. 3, pp. 1105-1106. Presented at the 30th Annual Meeting of the Division for Planetary Sciences of the American Astronomical Society, Madison, WI, October 16, 1998.
- J.M. Jenkins, B.J. Butler, P.G. Steffes, and M.A. Kolodner, "Retrievals of Sulfur-Bearing Gas Abundances from Microwave Emission Maps of Venus Obtained at the VLA," Bulletin of the American Astronomical Society, vol. 30, no. 4, pp. 1340. Presented at the 30th Annual Meeting of the Division for Planetary Sciences of the American Astronomical Society, Madison, WI, October 16, 1998.
- J.P. Hoffman and P.G. Steffes, "Preliminary Results of Laboratory Measurements of the Centimeter Wavelength Properties of Phosphine under Simulated Conditions for the Outer Planets," International Union of Radio Science Programs and Abstracts: 1999 National Radio Science Meeting, p. 286, Jan. 1999. Presented at the National Radio Science Meeting, Boulder, CO, January 7, 1999.
- J.P. Hoffman and P.G. Steffes, "Low Temperature Laboratory Measurements of the Centimeter Wavelength Properties of Phosphine under Simulated Outer Planet Conditions," Bulletin of the American Astronomical Society, vol. 31, no. 4, 1999. p. 1169. Presented at the 31st Annual Meeting of the Division for Planetary Sciences of the American Astronomical Society, Padova, Italy, October 14, 1999.
- P.G. Steffes, "Current Issues in Spectrum Management Affecting Radio Astronomy and Remote Sensing," International Union of Radio Science Programs and Abstracts: 2000 National Radio Science Meeting, p. 206, Jan. 2000. Presented at the National Radio Science Meeting, Boulder, CO, January 7, 2000.
- J.P. Hoffman and P.G. Steffes, "Laboratory Measurements of the Microwave Opacity of Phosphine: Opacity Formalism and Applications to the Atmospheres of the Outer Planets," Bulletin of the American Astronomical Society, vol. 32, no. 3, 2000. p. 1110. Presented at the 32nd Annual Meeting of the Division for Planetary Sciences of the American Astronomical Society, Pasadena, CA, October 26, 2000.
- P.G. Steffes, "Current Issues in Domestic Spectrum Management Affecting Radio Astronomy and Remote Sensing," International Union of Radio Science Programs and Abstracts: 2001 National Radio Science Meeting, p. 328, Jan. 2001. Presented at the National Radio Science Meeting, Boulder, CO, January 11, 2001.
- J.P. Hoffman and P.G. Steffes, "Laboratory Measurements of the Microwave Opacity of Phosphine: Opacity Formalism and Applications to the Atmospheres of the Outer Planets," Presented at the National Radio Science Meeting, Boulder, CO, January 9, 2001. (First Place for Hoffman in URSI Student Paper Competition.)